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THE DESIGN AND IMPLEMENTATION OF THE IMRI STRIP CASTER

J. Masounave, J. Blain, E. Essadiqi and S. Caron

Industrial Materials Research Institute
National Research Council Canada
75 De Mortagne
Boucherville, Quebec, Canada J4B 6Y4

Abstract

Increased competition in the steel producing market has led to a renewed interest in strip casting technologies. Current market trends would favor technologies capable of producing strips from 1 to 10 mm in thickness with a minimum of post processing.

To this end, IMRI has started a research effort aimed at producing a laboratory scale strip caster. This machine is being used to study the metallurgical aspect of twin-roll casting and to better understand the dynamics of twin-roll casters.

The "vertical twin roll" design was chosen for its simplicity, security, versatility, low cost and flexibility in thickness of the produced material. This paper gives a detailed discussion of the IMRI twin-roll strip caster. Particular attention is given to the thermal simulation of the process. The parameters examined include : the contact angle between the melt and the rolls, the heat transfer coefficient H, the roll speed, and the amount of superheat used when casting. The influence of these parameters on the strip exit temperature is discussed, as well as the problems associated with real time control of this process.

Typical microstuctures of strip-cast alloys are also presented and discussed with the aim of reducing post processing. Alloys were either strip cast in the IMRI twin-roll machine or on a moving-plate caster. Typical microstructures of 304 stainless steel, 1020 and 1010 plain C steels, copper alloys and aluminum alloys are presented. The influence of solidification times on microsegregation is discussed. The predictions from the computer model are in good agreement with experimental results. Heat tranfer at the melt - mold interface is very high during twin-roll casting when compared to planar single mold casting. This is caused by the presence of roll separating forces.

Introduction

After suffering a long depression period the steel industry is gradually regaining its dynamism and is once again looking at ways of improving its product and reducing its production costs. Patented in 1865 (1) but soon forgotten because of its technical complexity, strip casting of metals has recently resurfaced and is once again becoming a hot topic. In Canada, steel makers have recognised the immense advantages that could be realised by casting plates in thickness ranging from 1 to 10 mm, and are putting together a research program. The major goal of this program is to evaluate different methods of strip casting and to find the one best suited to casting steel sheet 1 to to 2 meters wide at a rate of 100 tons per hour.

As part of these efforts, IMRI has started a research program on strip casting (Table I). First a vertical twin-roll strip caster has been designed and built. Using this machine we are looking at the dynamics of strip casting and trying to identify the best way of controlling this somewhat unstable process. Among the questions we are trying to answer are:

What casting rates are possible?
What are the as-cast microstructures and mechanical properties?
Will hot or cold rolling be needed after strip casting?
What types of control sensors are needed?
What are the main material and engineering problems?
Is the process economically feasible?

Using aluminum and copper alloys, we have shown the feasibility of the process. Every alloy system selected is being or will be characterized in terms of microstructure and mechanical properties.

Table I. An Overview of the Evolution of the IMRI Strip Casting Project

1- Evaluation of different casting technologies in order to select the one best suited for IMRI's goals
2- National seminar sponsored by CSIRA to start national research program on strip casting
3- Design and construction of the IMRI twin-roll caster
4- Casting trials for aluminum and aluminum silicon alloys on solid copper wheels
5- Casting trials for aluminum silicon and copper based alloys on solid 4340 steel wheels
6- Design and construction of water-cooled casting wheels
7- Casting trials for copper alloys, stainless and carbon steels on the water-cooled rolls

The IMRI Twin-Roll Caster

Table II gives an overview of the current work being done world wide on strip casting. An examination of this table reveals the strengths and weaknesses of the different methods of producing metal strips:

a) Single-roll casting yields a strip with varying and non-symmetric microstructure through the thickness. Strip thickness is limited to no more than 3 or 4 mm and the casting rates are low due to limited heat transfer between metal and rolls. Planar flow casting is able to increase the casting rates but is still limited as to strip thickness and asymmetry of microstructure.

b) Twin-belt casters can produce, at very high rates, plates with minimum thickness of at least 10 mm. Because of belt warping due to thermal stress, it seems difficult to obtain thinner strips. Furthermore, the mechanical complexity of such machines cannot be overlooked.

c) Finally, twin-roll casters are able to cast strips in the right range of thickness (1 to 10 mm) with good surface finish. The challenge with this type of machine is to be able to produce at high enough rates and with minimum roll separation force to prevent roll damage.

TABLE II. Strip-Casting Technologies for Steels

Organization	Plate dimension Width-thickness (mm)	Casting processes	Casting speed (m/min)
Japan			
NSC	260 x 1	twin roll	
NKK	100 x (2 to 5)	twin roll	2 - 25
Sumitomo	600 x (20 to 80)	twin belt (Hazelett)	4 - 6
Kawasaki	200 x (0,1 to 0,4)	twin roll	180 - 720
	100 x 30	twin belt	0,5 - 12,5
	600 x (40 to 50)	twin belt	15 (anticipated)
Kobe	270 x (1 to 2)	twin roll	5 - 10
Nippon Metal	315 x (1 to 3)	twin roll	
United States			
Bethlehem/USS	1800 x (12 to 15)	twin belt (Hazelett)	9 - 12
Nucor	1300 x 40	twin belt (Hazelett)	
Allegheny-Ludlum	300 x (1 to 2)	single roll	
Armco/Westinghouse	75 x (0,7 to 3)	single roll	
National/Battelle	1800 x (0,25 to 4,5)	single roll	
LTV	250 x (2 to 5)	continuous casting	
SMS-CONCAST	1600 x 50	continuous casting	6
Europe			
BSC	400 x (1 to 25)	twin roll	
	500 x 50	casting train	10 - 13
CSM	300 x (1 to 25)	twin roll	
Krupp	200 x (20 to 70 mm)	twin belt (Hazelett)	10
IRSID	200 x (1 to 25)	twin roll	
Thyssen	1 mm	single roll	
Mannesmann Demag	600 x 20 mm	spray rolling process	
Schloemann-Siemag (SMS-CONCAST)	300 x 50 mm	standard equipment with convex mold	

The aluminum industry has shown that twin-roll casting is a metastable process (2) and that controlling the machine is a difficult task indeed. They have usually solved the problems by casting with steel cylinders at low speed and under high loads. This solution while effective in the case of aluminum alloys has to be rejected in the case of copper and steel alloys. The temperature of the plate would rapidly destroy the roll surface because of cracking.

For all of the above reasons, we decided to build a twin-roll machine at IMRI. The rolls were placed vertically because of the advantages this geometry brings:

a) Reduced risk of breaktrough
b) No need to bend the strip after it exits the machine
c) Reduced metal head at injection nozzle
d) More compact machine design

Experimental procedures

Twin-roll caster

Figure 1 shows a schematic representation of the machine. The rolls are 10 cm wide and 60 cm in diameter. Two types of rolls can be used, either OFHC copper or 4340 steel. The metal is fed to the rolls through a ceramic nozzle. The height of the nozzle opening varies depending on the experiment from 3 to 15 mm. Constant metallostatic pressure is maintained in the nozzle through the use of an overflow chamber. The bulk of the melt is maintained in a 200 kg capacity tundish and fed to the machine through a ceramic valve. Experiments have shown that this design gives us a temperature control of the melt to within ±2°C.

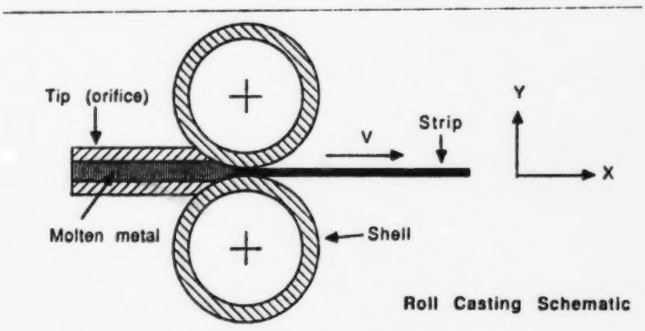

Figure 1 - Twin-roll strip caster (schematic)

The roll speed can be continuously varied from 0 to 16 RPM or from 0 to 80 RPM if a reduction gear box is removed. The maximum torque and load obtainable by this design are respectively 3400 N-m and 500 kN.

Therefore reduction between the rolls during casting is, by design, always limited. The tundish capacity and the fact that the rolls are not currently water cooled limits the possible strip length to about 30 m for 2 mm thick of brass. Roll temperature does not exceed 50°C throughout a test so that the strip solidification is not affected. Water-cooled rolls are being designed and will be used for steel strip casting.

The chemical composition of the alloys cast and the experimental conditions in the case of the steel rolls are given in Tables III and IV respectively. The physical properties of the above materials are summarized in Table V. The cast strips were 2, 1 and 0.5 mm in thickness and 10 cm in width for A380 alloy and 2 mm in thickness and 10 cm in width for brass 2600 alloy.

Moving-plate caster

In order to be able to generate some data for steel alloys before the twin-roll caster was completed, a horizontal moving-plate caster was also built. With this machine, carbon and stainless steel strips were produced by pouring the alloy directly onto the plate while the plate was moving with a velocity of 0.5 m/s. The chemical composition and the experimental conditions are given in Tables VI and VII.

Table III. Chemical Compositions (wt.%) of Aluminum and Copper Alloys

Material	Si	Cu	Zn	Fe	Mg
1060 Al Alloy	.07	—	0.01	0.18	--
380 Al Alloys	9.16	3.25	2.41	0.84	0.05
Brass	--	70	30	--	--

Table IV. Casting Conditions for Aluminum and Copper Alloys Cast on Steel Rolls

Speed (RPM)	Liquid Temperature T°C	Contact Angle, θ	Strip Thickness, mm	Heat Transfer Coefficient H $W/m^2 \cdot K$
14.5	610	7.5	0.5	10000
7.5	617	7.5	1.0	8500
5.0	617	11.0	2.0	8500
13.0	995	11.0	2.0	10000

Table V. Physical Properties of 380 and 1060 Al Alloys (3,4)

Material	A380	Brass
Density, ρ (kg/m^3)	2740	8530
Liquidus T_L (°C)	572*	955
Solidus T_S (°C)	550*	915
Latent heat (kJ/kg)	389	203
Specific heat, Cp (J/kg•K)	963	375
Thermal conductivity,K (W/m•K)	96.2	120

*these values have been determined experimentally.

Table VI. Chemical Composition (wt.%) of Steels Cast on Moving Plate

Steel	C	Mn	Si	Cr	Ni	P	S	Al	N_2
Carbon steel 1010	0,08	0,38	0,08	0,01	0,02	0,008	0,011	0,02	0,0016
Carbon steel 1020	0,18	0,7	0,01	0,03	0,01	0,005	0,01	0,02	0,0018
Stainless steel 304	- 0,05	1,81	0,53	18,3	8,39				

Table VII. Experimental Conditions of Plain C 1010, 1020 and Stainless Steel 304

Material	Melting Temperature (°C)	Pouring Temperature (°C)
Plain C 1010	1630	1550
Plain C 1020	1620	1540
Stainless Steel 304	1500	1480

Computer modelling of the process

Because the process is metastable and because one of our goals is to automate the strip production, a computer program was written to simulate the process. This two-dimensional simulation predicts heat flow and temperature within the cast strip and rolls. Work is also under way in collaboration with Noranda Research Center to incorporate a mechanical simulation but only the thermal analysis will be presented here.

The simulation is based on the explicit finite difference method. The formulation used in cylindrical coordinates is as follows:

For the element's tangential face:

Conduction $$\left(\frac{K\Delta\theta}{\Delta R}\right)\left(R_o + \frac{\Delta R}{2}\right)\left(T_1 - T_o\right) = Q \qquad (1)$$

Convection $$\left(H_1\Delta\theta\right)\left(R_o + \frac{\Delta R}{2}\right)\left(T_1 - T_o\right) = Q \qquad (2)$$

Radiation $$\varepsilon\sigma\Delta\theta\left(R_o + \frac{\Delta R}{2}\right)\left(T_1^4 - T_o^4\right) = Q \qquad (3)$$

For the element's radial face:

Conduction $$\left(\frac{K\Delta R}{R_o\Delta\theta}\right)\left(T_2 - T_o\right) = Q \qquad (4)$$

Unit volume temperature variation with time:

$$\Delta T = \frac{Q\Delta t}{\rho\ \Delta\theta\ R_o\Delta R\ Cp} \qquad (5)$$

where: H is the heat transfer coefficient, ε is the material's emittance, σ is the Stefan-Boltzmann constant, Q is the heat, Δt is the time increment and ΔT is the temperature increment.

The current program can be used to simulate either single or twin-roll casting. The phase change and the solid fraction are obtained by using the equivalent specific heat method (5) and by assuming a linear relationship between temperature and the amount of solid phase present. Although not rigorously correct, these hypotheses enable adequate simulation of the process even in the absence of complete thermodynamic data for the cast material.

The model permits the use of temperature-dependent material properties such as thermal conductivity, specific heat and density. However, experience has shown that using constant values equivalent to those near the melting point decreases the software runtime by an order of magnitude without significantly changing the simulation results. Thus these values were kept constant and are given in Table V. The heat transfer coefficient, H, can also be made variable along the contact angle between the strip and the rolls. We kept it constant for our simulation because the predictions were in good agreement with the results and because there is a lack of accurate data on the subject.

The boundary conditions used for the mesh are straightforward (Figure 2):

- The surface of the mesh which corresponds to the strip center has a heat flux of zero.
- The heat flux through the bottom of the mesh (the interface between the strip and the roll) is set by the heat transfer coefficient and the temperature difference between the roll surface and the strip surface.
- The input temperature is set equal to the temperature of the melt inside the injection nozzle.
- The radial temperature gradient is assumed to remain constant after the last node.

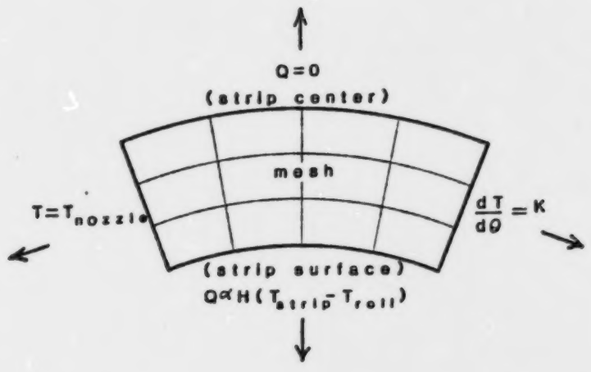

Figure 2 - Boundary conditions for the mesh

Because some of our strip casting is also done on moving plates, another program using the same techniques but in rectangular coordinates was developed. This program was used to determine the heat transfer coefficient corresponding to the cooling rates observed during the plate solidification.

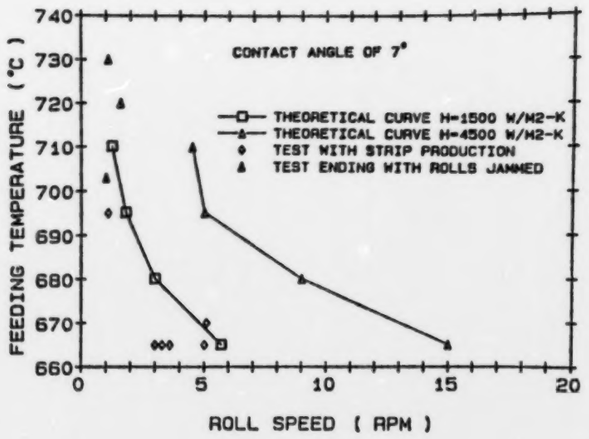

Figure 3 - Comparison between experiments and computer simulation for the casting of pure aluminum

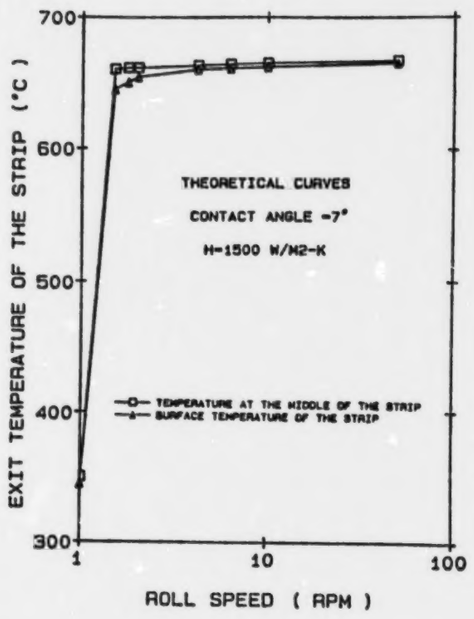

Figure 4 - Model prediction of the exit temperature of a strip of pure aluminum.

Automating the process

From the previous discussion it is clear that in order to be successful, twin-roll strip casting must be automated. Up to now, our machine has been controlled manually during the aluminum and copper casting. However, we have also been monitoring different process parameters. These parameters can be separated into two groups : the control variables which can be adjusted during production (speed, nozzle temperature) and the feedback variables that act as warning signals (force, torque, exit temperature, etc.).

Our main control variable up to now has been the roll speed and our main feedback variable the roll separation force. A typical illustration of one of our tests is given in Figure 5. At the onset of the test, the roll speed is set to the maximum. In this way, the first metal to come out of the rolls will be liquid. After 10 to 30 sec the nozzle injection temperature has stabilised and the roll speed is gradually decreased. In the present test, aluminum strip, rigid enough to be handled, started coming out of the machine at 12 RPM. The graph shows a clear relationship between the roll torque and the casting speed. The minimum speed used in this run was 5 RPM. This speed yielded torque measurements of 100 N•M and a roll loading not higher than 1 kN. During this three minute test approximatly 25 to 30 meters of strips were produced.

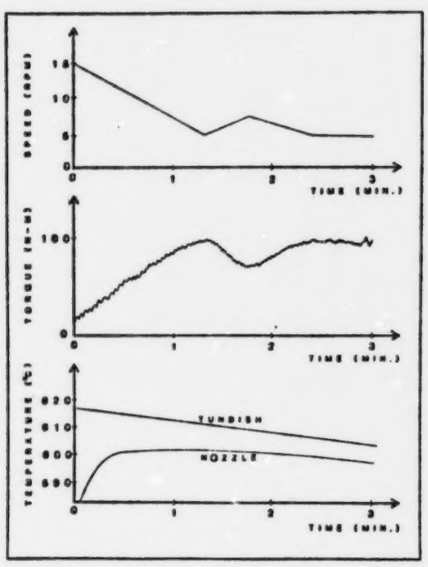

Figure 5 - Typical runout casting of 25 m of A380 2mm strip.

This test is typical of the results we have obtained to date. It clearly shows that the process can be controlled by using the roll speed to set the condition. Either the torque or the roll separating force can be used as a feedback signal to set the speed. We believe that for our purpose, the separating force is a more accurate signal. This force in effect signals the presence of solid (rigid) material between the rolls. On the other hand the torque is more a measure of where this solid material

is in relation to the roll pinch.

Although annoying, the existence of the critical speed also gives us another very good feedback parameter. By continuously measuring the strip exit temperature, one can control the casting rate so as to maintain the strip quality at a constant level. We are currently installing a two color pyrometer and will shortly be able to try out this concept.

Microstructure results

Twin Roll.

A380 Aluminum Alloy. A typical structure of a transverse section of a 2 mm strip close to the surface of the wheel at a quarter thickness and at the centre is shown in Fig. 6a-c. It consists of dendrites of aluminum solid

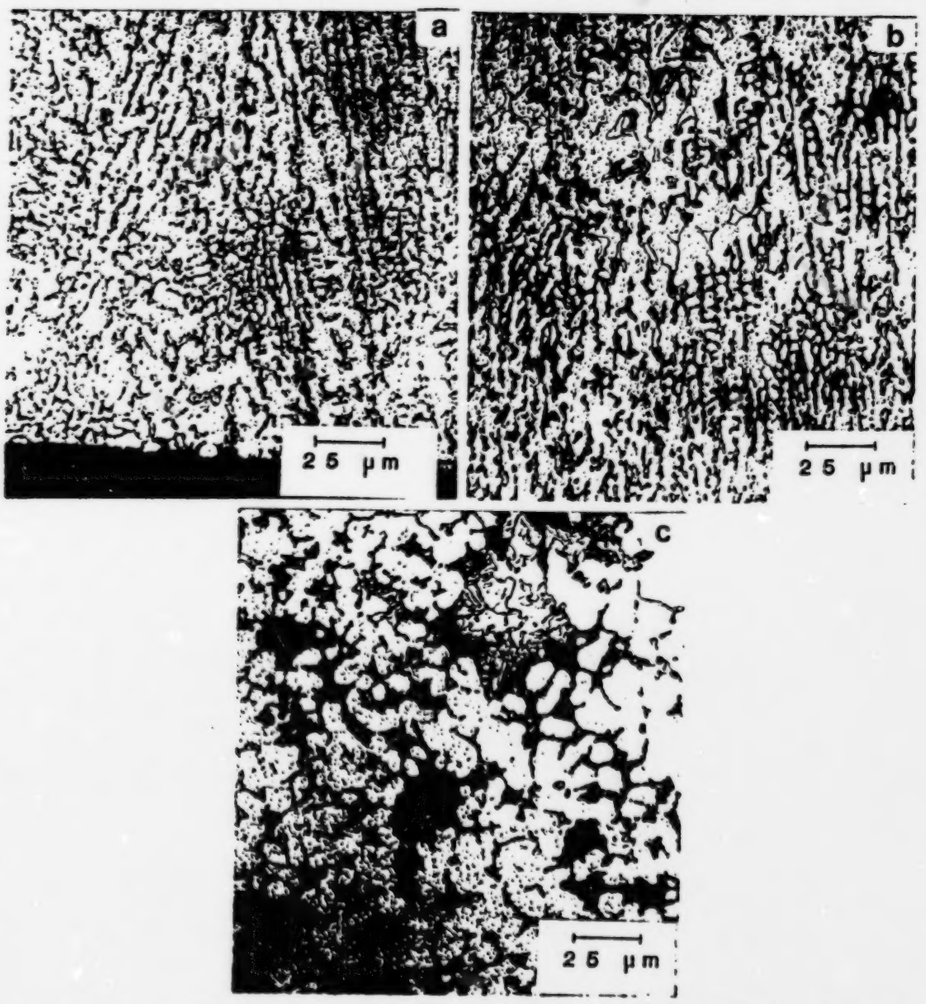

Figure 6a-c - Solidification structure of as cast A380 aluminum alloy, a) close to the wheel surface, b) at quarter thickness and c) at the centre of a strip.

solution (white areas) with a eutectic Al-Si-Al_2Cu in the interdendritic spaces. The silicon is dark and the intermetallic compound Al_2Cu is grey. The primary dendrites are parallel to the heat flow (Fig. 6a-b). In the central zone the structure is equiaxed (Fig. 6c). It covers about 0.6 mm in thickness. The secondary dendrite arm spacing (SDAS) becomes coarser as the distance from the wheel surface increases from zero to the half thickness of the strip. The SDAS varies from 3 to 6.5 μm in the region of the strip that was completely solidifed at the moment when it exited the twin rolls. In the central area, it varies from 7 to 12 μm.

It is well known that decreasing the cooling rate (increasing the solidification time) leads to coarser dendrite arm spacing. In this case the segregation at the centre of the strip becomes more significant. Also, some porosity has been observed through the thickness particularly in the central zone.

In the case of 1 mm thick strip, the characteristic structure is shown in Fig. 7a-b. As before, two zones are observed. Close to the wheel surface the dendritic structure is fine and parallel to the heat flow; the SDAS varies from 2 to 5.5 μm. At the centre, the structure is equiaxed and coarse; the SDAS varies from 5.5 to 9 μm. This zone covers about 0.2 mm. This indicates that the strip was not completely solid when it left the rolls. It is shown (Fig.13) that 0.2 mm in thickness at the centre of the strip was in the mushy zone. As opposed to the strip of 2 mm thickness, the 1 mm strip showed only little porosity.

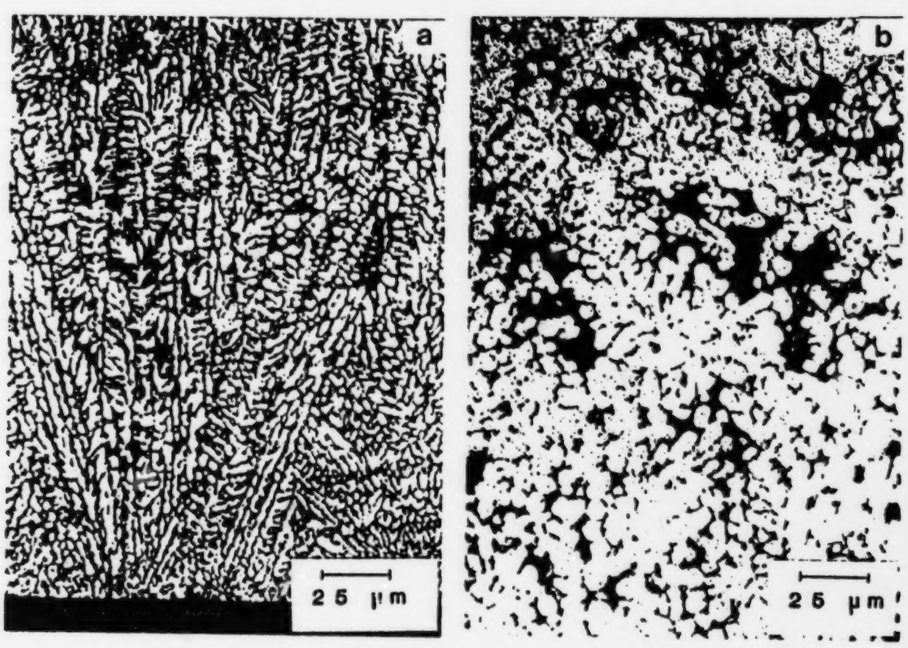

Figure 7a-b - Solidification structure of as-cast A380 aluminum alloy, a) close to the roll surface and b) at the centre of the strip 1 mm in thickness.

For 0.5 mm thick strip, the structures close to the wheel surface and the central zone are shown in Fig. 8a-b respectively. They are similar to

those of 1 mm thick strip, however the strip was completely solid at the exit from the caster. The SDAS varies in the range 2 to 3.5 μm from the wheel surface to the centre of the strip.

At the exit, the mushy zone at the centre of the cast strip decreases from 1/3 of the thickness to 1/5 to zero as the thickness of the strip decreases from 2 to 1 mm to 0.5 mm. The structure is also finer, which indicates an improvement of the microsegregation with the smallest thickness.

Copper Alloys. Two zones have been observed in the 2 mm strip of brass: close to the surface an undercooled zone of about 40 μm in thickness followed by a columnar dendritic zone through almost half of the strip thickness (Fig. 9a). At the centre of the strip there is a boundary resulting from the intersection of the two solidification fronts (Fig. 9b). This indicates that the strip was almost completely solid at the exit from the twin rolls. The structure shows α dendrites (white areas). The interdendritic regions (dark areas) are rich in Zn. The secondary dendrite arm spacing varies in the range 3 to 6 μm from the wheel surface to the centre of the strip. Cu-Ni-Sn was also strip cast; the solidification structure illustrated by Fig. 10 is similar to that of the brass (7).

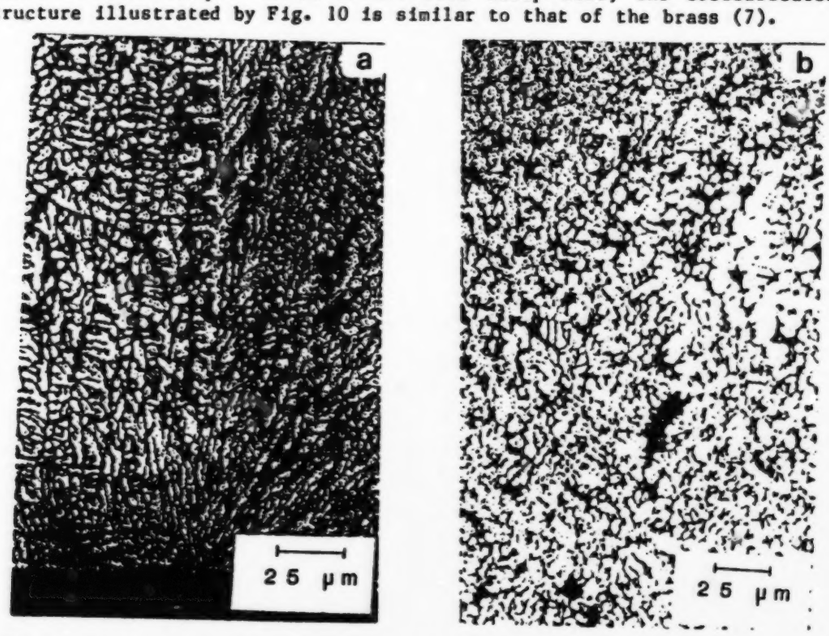

Figure 8a-b - Solidification structure of as-cast A380 aluminum alloy, a) close to the surface and b) at the centre of the strip 0.5 mm in thickness.

Moving Plate. Different materials such as 304 stainless steel, 1010 and 1020 plain C steel and Cu-Ni-Sn alloys were cast on the moving copper plate with a speed of 0.5 m/s. Fig. 11 gives a typical structure of 304 stainless steel which shows the classical three zones: undercooled, columnar and equiaxed respectively. The SDAS varies from 4 to 12 μm. The other materials present a similar solidification structure (8-10).

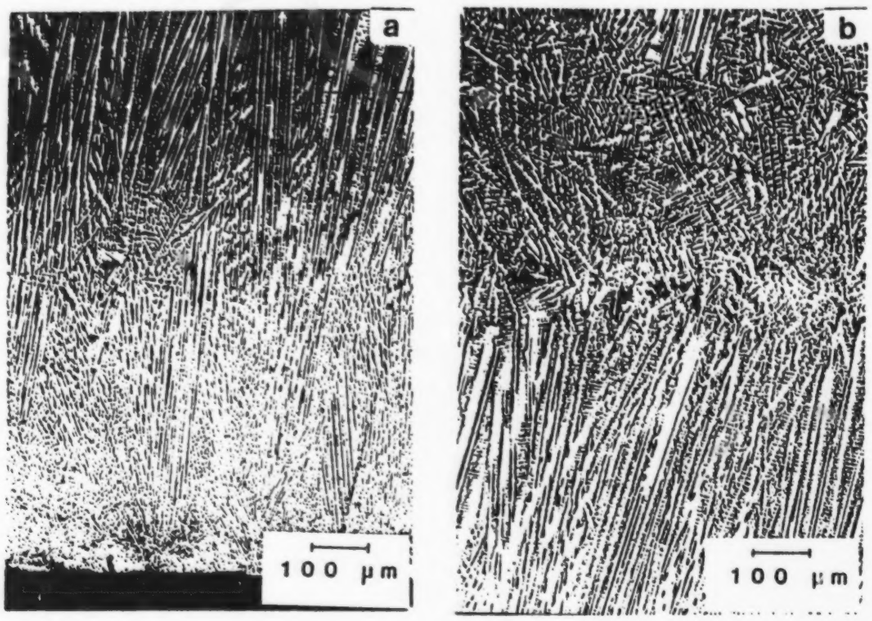

Figure 9a-b - Solidification structure of brass a) close to the wheel surface and b) at the centre of the strip 2 mm in thickness

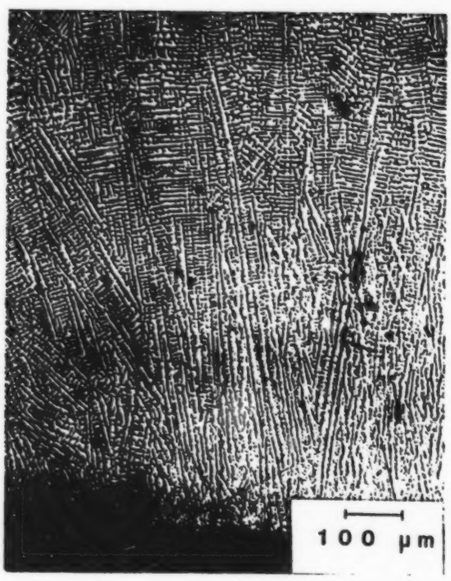

Figure 10 - Solidification structure of as-cast C72500 alloy, 1 mm in thickness.

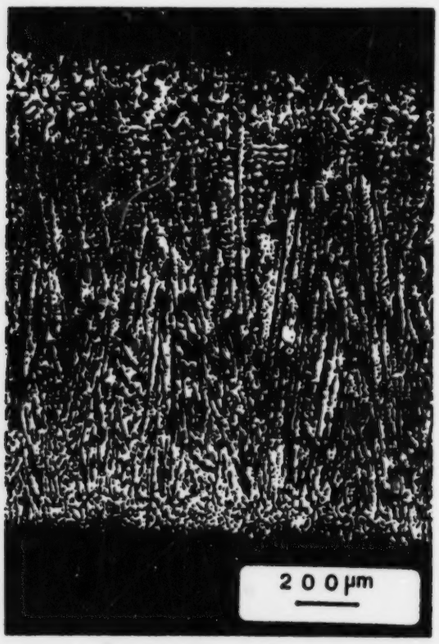

Figure 11 - As-cast structure of 304 stainless steel across the thickness, cast on the moving copper plate.

General Discussion

As stated earlier, one of the goals of the Canadian research program on strip casting is to identify strip casting technologies capable of sustained production rates of 100 tons/hour. While we have not yet produced steel strips , we can get a good idea of the capabilities of our machine by using the data from the Al - Si and Cu - Zn alloy trials.

Solidification time

A dendritic structure is characteristic of all aluminum alloy and copper alloy casting. The mechanical properties of cast alloys are influenced by the dendrite arm spacing (11-15).

A380 Alloy. The relationship between the solidification time t_f and the secondary dendrite arm spacing for 380 alloy strip cast by our twin-roll system has been established as follows (16).

$$\lambda = 10.10\ t_f^{0.43} \qquad (6)$$

where λ is the dendrite arms spacing (μm) and t_f is the solidification time (s). The solidification times t_f estimated from the SDAS measurements by using the above equation are given in Table IX.

For the strip 2 mm in thickness, the solidification time varied from 0.06 to 0.36 s in the columnar zone, which was solid at the exit from the twin rolls. The latter value corresponds to the residence time between the

rolls and thus to a speed of 5 RPM which is in agreement with the experimental conditions. The solidification time corresponding to the central zone varies from 0.43 to 1.5 s which means that the strip was completely solid one second after the exit. In the case of 1 mm thick strip the solidification times in the columnar zone (completely solid at the exit from the wheel) varies from 0.02 to 0.19 s and in the mushy zone from 0.24 to 0.76 s. The value of 0.19 s is close to the experimental residence time (0.16 s) of the strip 1 mm in thickness. For the 0.5 mm thick strip the solidification time varies from 0.02 to 0.09 s. The latter value corresponds to the residence time of the strip between the rolls. It corresponds to a speed of around 14 RPM. This value is close to the experimental one (14.5 RPM). In order to have the strip 2 and 1 mm in thickness completely solid at the exit of the twin roll, at a given contact angle, the speed must be described.

Brass. A relationship between secondary dendrite arm spacing and solidification time for brass was estimated from the literature data (17):

$$\lambda = 10.40\ t_f^{0.35} \qquad (7)$$

In brass the SDAS were 3 and 6 μm close to the wheel surface and at the centre respectively. The corresponding solidification times were 0.03 and 0.20 s. The latter value is higher than the experimental residence time of the strip between the rolls (≈ 0.13 s).

304 Stainless Steel Cast on a Moving Plate. In the case of 304 stainless steel, the relationship between the SDAS and the solidification time is expressed as follows (9):

$$\lambda = 15.42\ t_f^{0.347} \qquad (8)$$

The solidification times corresponding to 4 and 12 μm were 0.02 and 0.48 s respectively. Lower values of SDAS and solidification time can be expected in the case of the twin-roll process because of the higher heat transfer coefficient. It was found also, that there was no macrosegregation; however a low degree of microsegregation of Cr and Ni was observed during this process.

Table IX. Solidification Time and SDAS for the A380 Alloy Strip Cast in Different Thicknesses.

Strip thickness	Zone	SDAS (μm)	t_f (s)
2 mm	solidified zone	3 - 6.5	0.06 - 0.36
	mushy zone	7 - 12	0.43 - 1.5
1 mm	solidified zone	2 - 5	0.02 - 0.19
	mushy zone	5.5 - 9	0.24 - 0.76
0.5 mm	solidified zone	2 - 3.6	0.02 - 0.09

Heat transfer coefficient

Table IV gives typical casting conditions for these alloys. Using our computer program we tried to find a heat transfer coefficient corresponding to our results. The main problem here is the fact that we do not know exactly how much of the exit strip is completely solidified. Micrographs taken from A380 strips clearly show that in some cases half of the strip coming out was still in a mushy state while in other cases solidification was complete.

The best example of this latter case is given by the 0.5 mm A380 strips (Fig. 12). In this case the machine produced about 5 m of solid strip at a speed of 14.5 RPM before jamming. Thus we know that this corresponds roughly to the critical speed. Using this data we were able to conclude that the heat transfer coefficient needed to complete the strip solidification before or at the roll pinch was 10 000 $W/m^2 \cdot K$. This is also consistent with simulations of tests for 1 and 2 mm thick aluminum strip. In these cases micrographs show that solidification was only complete through about 4/5 (1 mm, Fig. 13) and 3/5 (2 mm) of the strip thickness. The simulation tells us that this corresponds to a heat transfer coefficient of around 8500 $W/m^2 \cdot K$ in both cases. Thus as long as the strip is not completely solid in between the rolls the heat transfer is reduced.

Another interesting point to make is that when producing brass strip, we were able to cast at speeds of 13 RPM. In this case micrographs (Fig. 9) show that almost all of the plate was solidified between the rolls. This corresponds to a heat transfer coefficient of 10000 $W/m^2 \cdot K$. Even though the roll separation force was very low during this test, there still was good heat exchange. This leads us to believe that even higher values of H could still be obtained. After all, H values of 100 000 $W/m^2 \cdot K$ can be observed during chill block melt spinning of ribbon $\sim 1\mu$ thick (18).

Casting rate prediction. Using the 10000 $W/m^2 \cdot K$ value, we can predict the casting rate for a low carbon steel 2 mm thick strip, cast on our rolls, with a contact angle of 10°. In this case, the program gives a critical speed value of around 6.5 RPM. Given a typical industrial width of 2 meters this would yield a casting rate of 23 tons/hr.

Keeping all parameters the same and doubling the roll radius, would double the casting rate. Thus, two twin-roll machines with rolls of 1.2 meters in diameter would be able to meet the rates required by the Canadian steel makers. Since a vertical twin-roll design does not require large floor space the use of two machines in parallel would not be problematic.

Impact of surface quality

One remaining problem though is how assure that the heat transfer is uniform over the whole contact surface. If this condition is not met and the machine is operated near the critical speed, surface defects similar to those reported by aluminum (2) producers are bound to appear. Work needs to be done on that aspect. From our own experience, graphite coatings are not a very good solution because their lubricating characteristics promote slippage between the roll and the strip. Heat transfer is reduced and in the worst case the rolls can completely loose contact with the strip for short periods of time. Work is under way to look at different materials that could act as coatings. We also now have machinery to enable us to change the roll surface roughness in an effort to find the best surface condition.

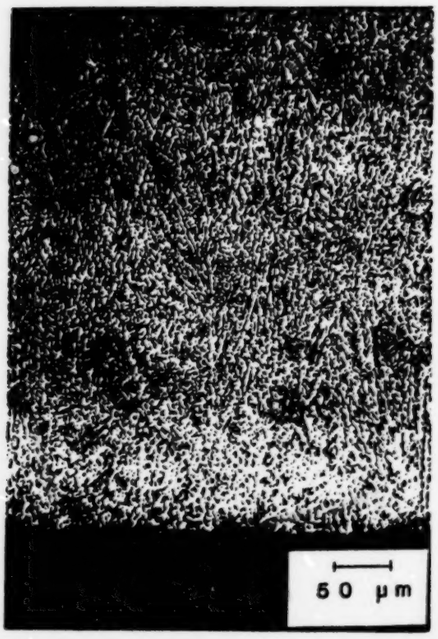

Figure 12 - As-cast structure of 0.5 mm A380 alloy strip

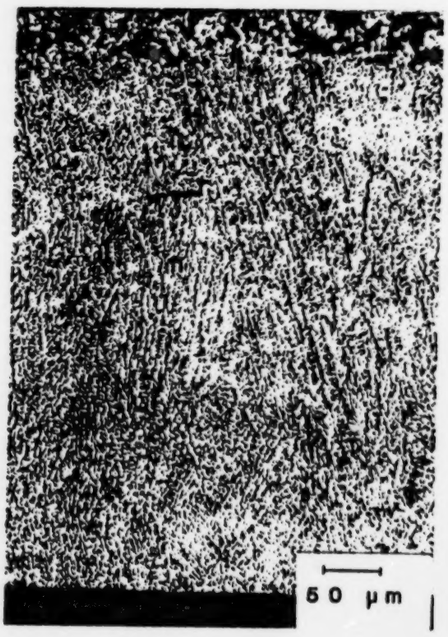

Figure 13 - As-cast structure of 1 mm A380 alloy strip

Conclusion

The current results of our investigations clearly show that:

- Vertical twin-roll casters are capable of casting aluminum and copper based alloys in strips of from 0.5 to 3 mm thickness.

- The heat exchange computer model we developed gives accurate predictions.

- The heat transfer coefficient at the strip - roll interface can be quite high (10 000 $W/m^2 \cdot K$) if a minimum amount of roll separation force is present.

- Manual control of the process is feasible only if the strip is not completely solid in or before the roll pinch.

- The best feedback parameter seems to be the roll separation force.

- Extrapolation from the current results indicates that a 2 m wide steel casting machine with 60 cm rolls would be able to cast steel strip at a rate of 20 tons/hr with a contact angle of 10°.

- Some effort has to be made to identify optimal roll surface conditions to promote heat exchange, avoid slipping and thus improve surface quality of the strip.

Once these steps are completed, we will be able to look at the microstructure and mechanical properties of strip-cast steels. The goals here will be to find the shortest path in terms of thermomechanical working to obtain deep drawing quality steel.

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